REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
May, 2001

3. REPORT TYPE AND DATES COVERED
Final 01 May 96 – 30 Apr 00
~~5/96 – 12/99~~

4. TITLE AND SUBTITLE
Modeling and Analysis of Electromagnetic Coupling Through Apertures Into Complex Systems

5. FUNDING NUMBERS
G DAAH04-96-1-0087

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
35568-EL-SAM
.6

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Three related technical areas associated with modeling of electromagnetic coupling into complex systems were examined. The first area was the development of hybrid numerical models for modeling shielded enclosures containing wires of arbitrary orientation and shape and the shield containing tortuous path apertures. The second area was the modeling of very large cavities using domain decomposition methods. The third and final area was the accurate modeling of transient electromagnetic phenomena using methods borrowed from computational fluid dynamics. With varying degrees of success, progress was made in each area in advancing the state-of-the art. This was especially true in the development of the hybrid numerical methods and modeling of transient electromagnetic phenomena. In addition, the effort resulted in several publications as well as the graduation of several students.

14. SUBJECT TERMS

15. NUMBER OF PAGES
9

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Modeling and Analysis of Electromagnetic Coupling Through Apertures Into Complex Systems

ARO Grant #DAAH04-96-1-0087

Final Report To

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May 21, 2001

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1 Project Statement

Electromagnetic coupling can adversely impact a multitude of applications ranging from modern telecommunication systems to sophisticated electronic warfare equipment. In these applications, the primary coupling issues are electromagnetic compatibility and interference, either intentional or unintentional. The functionality of systems involved, which typically consist of numerous subsystems operating concurrently, can be characterized in terms of their susceptibility, vulnerability and survivability to the coupling phenomena inherent in the electromagnetic environment in which they are expected to operate.

The work completed under this project focused on developing computational models and algorithms for modeling coupling into realistic, complex systems. The coupling considered was through apertures in a shield surrounding the system that were present due to the method of construction. In particular, we considered the following:

- Coupling into complex cavities having imperfectly conducting walls and containing inhomogeneous, imperfectly conducting dielectrics. The cavity may contain wires with an arbitrary orientation,
- Coupling into very large cavities for which conventional methods do not allow a solution on a normal desktop workstation, and
- Modeling of transient electromagnetic waves propagating in inhomogeneous materials.

The following sections will detail the work done for each of these areas.

2 Summary of Important Results

2.1 Coupling Into Cavities Containing Wires With Arbitrary Orientation

The work in this area is an extension of work originally done for Sandia National Laboratories in which a hybrid algorithm combining the finite element method (cavity interior and walls) and the method of moments (narrow, tortuous-path slot aperture) was used to calculate the coupling into an arbitrary cavity. The result of the original hybrid algorithm was the PhD dissertation of Russel Jedlicka [8], [9]. The slot model of Warne and Chen [1] - [7] is used to model the narrow slot aperture. The slot model includes the wall losses of the conductors as well as homogeneous, lossy dielectrics that may fill the slot interior. The limitation of the slot model is that the slot width is much smaller than a wavelength.

Brian Lail extended Warne and Chen's model by including a straight conducting wire of finite radius by a ground plane with a slot with the result being his MSEE degree. A journal paper detailing this work was published [10]. The limitation of this model was that the wire had to be placed orthogonal to the slot and parallel to the ground plane containing the slot.

Work is currently proceeding on extending Lail's original work by:

- Including the general cavity model of Jedlicka with the wire and slot and,
- Placing the wire in an arbitrary orientation and position relative to the slot.

It is expected that Brian Lail will complete his PhD degree in August of 2001 as a result of these two extensions to his original work.

2.2 Coupling Into Very Large Cavities Using the Connection Method

In many cases a large cavity cannot be modeled on a computer because of the limitations of memory and CPU time. Therefore, it is necessary to use some type of domain decomposition for modeling very large three-dimensional cavities. This work has application not only in system vulnerability assessment, but in RCS prediction work as well in which an aircraft engine inlet can be modeled as a complex cavity.

In this effort, John Loukota used the connection method of Wang and Ling [11] to model large two-dimensional conducting cavities with a finite-element formulation. The connection method is essentially a special case of domain decomposition in which each subregion of the cavity is modeled by the finite element method. The aperture admittance matrix is extracted from the resulting finite element equations. The subregion admittance matrices are cascaded to yield an overall admittance matrix at the aperture of the cavity. Mr. Loukota then used a moment method to discretize the aperture (in a conducting ground plane) together with the admittance matrix to solve for the unknown aperture currents. The coupled fields into the cavity are calculated by propagating the aperture solution back into the cavity using the subregion admittance matrices.

Mr. Brad Millard continued Mr. Loukota's work by extending the method to a full three-dimensional cavity. Rather than writing a code for modeling the exterior and aperture of the cavity, Mr. Millard attempted to modify the Carlos-3D method of moments code from the Electromagnetic Code Consortium (EMCC) so that an "impedance surface" derived from the calculated admittance matrix of the cavity could be used directly in Carlos-3D. Mr. Millard left NMSU in the middle of this research effort leaving the work unfinished.

2.3 Modeling of Transient Electromagnetic Waves Propagating in Inhomogeneous Materials

The numerical modeling of the behavior of electromagnetic waves in the time domain has application in many areas of electromagnetics. However, the dual effects of numerical dispersion (phase errors), and numerical diffusion (amplitude errors) limits the applicability of many popular numerical methods - especially for very large numerical problems. In addition, most of the popular numerical methods for solving the differential form of Maxwell's equations are limited by their structure (FDTD) or mesh generation complexity (finite element).

Earlier work by Steve Omick at NMSU [12] had borrowed heavily from the large body of computational fluid dynamics (CFD) in a successful attempt to eliminate numerical dispersion for modeling transient electromagnetic fields. This work was applied to both finite element and finite difference solution of Maxwell's equations. However, the methods developed by Dr. Omick were still limited to defined grids.

Steffany Buckles developed the use of an adaptive meshless method used in computational fluid dynamics to solve both problems of numerical dispersion (by using an adaptive method) and grid restrictions. The Smoothed Particle Hydrodynamics (SPH) numerical method for modeling hydrodynamic problems used by Ms. Buckles is a gridless method first described by Lucy in 1977 [13].

Ms. Buckles was able to model both one-dimensional transmission-line problems and two-dimensional transverse magnetic (TM) scattering problems with transient time variations using a generalization of the SPH method combining adaptivity to minimize dispersion and a Perfectly Matched Layer (PML) so that infinite, open-region problems could be considered.

A journal publication summarizing this work is now in preparation.

2.4 Impact of Research Funding on NMSU and PI

The research funding played a key role in extending some of the earlier work of the PI's. In addition, several students benefitted from the funding, having obtained advanced degrees and going on to employment in areas of high need in the national economy. Most importantly, the importance of the work is underscored by the continued funding currently being received from Sandia National Laboratories. Applications of interest now being considered include the examination of metallic plumbing in nuclear power plants using non-invasive microwave methods as well as vulnerability assessment for very complex systems. The PI's are extremely grateful for the support provided by the Army Research Office for this work.

3 Listing of Publications

3.1 Conference Publications

1. S. Buckles and S. Castillo, "The Use of Meshless Methods for Solving Electromagnetic Vector Scattering problems," Proceedings of the 1999 IEEE International Symposium on Antennas and Propagation, July, 1999.

2. S. Buckles and S. Castillo, "The Application of Meshless Methods to the Numerical Solution of Transient Electromagnetic Field Problems," Proceedings of the 1998 IEEE International Symposium on Antennas and Propagation, July, 1998.

3. B. Lail and S. Castillo, "Electromagnetic Coupling Through Narrow Slot Apertures Into a Half-Space Containing a Conducting Element," Proceedings of the 1998 IEEE International Symposium on Antennas and Propagation, July, 1998

4. J. Loukota, S. Castillo. J. Millard, and R. Jedlicka, "Analysis of Large Cavity Field Problems Using a Finite Element Formulation of the Connection Scheme," Proceedings of the 1997 International IEEE/AP-S Symposium.

5. R. Jedlicka and S. Castillo "Electromagnetic Coupling into Complex Cavities Through Narrow Slot Apertures Having Depth and Losses," Proceedings of the 1996 International IEEE/AP-S Symposium.

3.2 Journal Publications

1. S. Buckles and S. Castillo, "An Adaptive Meshless Method for Solving Transient Electromagnetic Scattering problems," to be submitted to the *IEEE Transactions on Antennas and Propagation*, in preparation.

2. B. Lail and S. Castillo, "Coupling Through Narrow-Slot Apertures to Thin-Wire Structures," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 42, No. 3, pp. 276-283, August, 2000.

3. R. Jedlicka, S. Castillo, L. Warne, "Coupling Through Tortuous Path, Narrow Slot Apertures into Complex Cavities," *IEEE Transactions on Antennas and Propagation*, Vol. 48, No. 3, pp. 456-466, March, 2000.

4 Listing of All Participating Scientific Personnel

- Steffany Buckles, MSEE 1999, currently employed at Ball Aerospace, Boulder Colorado, MS thesis title - "The Application of Smoothed Particle Hydrodynamics to the Numerical Solution of Transient Electromagnetic Field Problems".

- Steven Castillo, PI, Professor and Department Head, Klipsch School of Electrical and Computer Engineering, New Mexico State University.

- Russell Jedlicka, Co-PI, Assistant Professor, Klipsch School of Electrical and Computer Engineering, New Mexico State University.

- Brian Lail, MSEE 1998, currently employed in the Klipsch School of Electrical and Computer Engineering at NMSU, MS thesis title - "Electromagnetic Coupling Through Narrow Slot Apertures Into a Half-Space Containing a Conducting Element", current status - all classwork completed, qualifying exam, PhD proposal and comprehensive exam completed, research, dissertation, and final oral exam to be completed, Proposed PhD dissertation title - "Electromagnetic Coupling Through Narrow-Slot Apertures to Thin-Wire Structures", expected PhD completion date - 9/01.

- John Loukota, MSEE 1996, currently employed at Motorola, Inc., Mansfield MA, MS thesis title - "Two-Dimensional Coupling Into Large Cavities Using the Connection Algorithm".

- Brad Millard, MSEE degree not completed, current employment unknown, proposed MS thesis title - "Three-Dimensional Coupling Into Large Cavities Using a Finite Element Formulation of the Connection Algorithm", current status - research not completed, classwork completed, thesis not completed.

- Charles Salazar, MSEE degree not completed, currently employed at Motorola, Inc., Phoenix AZ, proposed MS thesis title - "The Use of Multigrid Methods for Solving Electromagnetic Field Problems", current status - all classwork and research completed, thesis not completed.

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[2] Warne, L.K. and K.C. Chen, "Equivalent Antenna Radius for Narrow Slot Apertures having Depth," *IEEE Transactions on Antennas and Propagation*, Volume AP-37, No. 7, July 1989, pp. 824-834.

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ing Depth," *IEEE Transactions on Electromagnetic Compatibility*, Volume EMC-30, No. 3, August 1988, pp 364-370.

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[7] Warne, L.K. and K.C. Chen, "Effective Impedance of Bolt Loads on Narrow SlotApertures Having Depth," *Journal of Electromagnetic Waves and Applications*, Vol. 6, No. 7, 1992.

[8] R. Jedlicka, *Electromagnetic Coupling into Complex Cavities Through Narrow Slot Apertures Having Depth and Losses*, PhD. Dissertation, Klipsch School of Electrical and Computer Engineering, New Mexico State University, Las Cruces, NM, December 1995.

[9] R. Jedlicka, S. Castillo, L. Warne, "Coupling Through Tortuous Path, Narrow Slot Apertures into Complex Cavities," *IEEE Transactions on Antennas and Propagation*, Vol. 48, No. 3, pp. 456-466, March, 2000.

[10] B. Lail and S. Castillo, "Coupling Through Narrow-Slot Apertures to Thin-Wire Structures," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 42, No. 3, pp. 276-283, August, 2000.

[11] T. Wang and H. Ling, "Electromagnetic Scattering from Three-Dimensional Cavities Via a Connection Scheme," *IEEE Transactions on Antennas and Propagation*, Vol. AP-39, No. 10, pp. 1505-1513, October, 1991.

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